Low-wavenumber pedestal turbulence in NSTX: measurements, parametric scalings, and simulations

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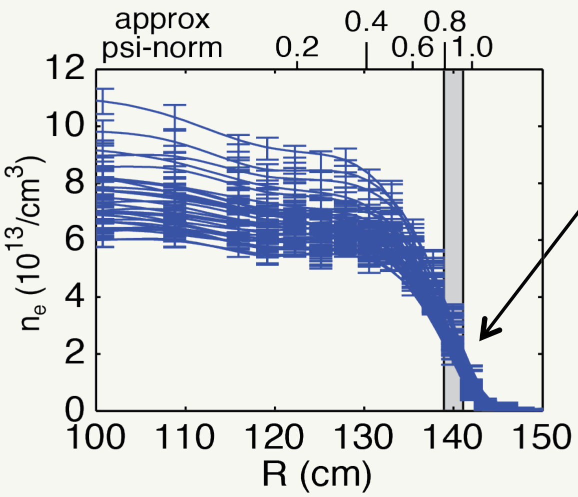
US-EU Joint TTF Workshop
Santa Rosa, CA
April 8-12, 2013

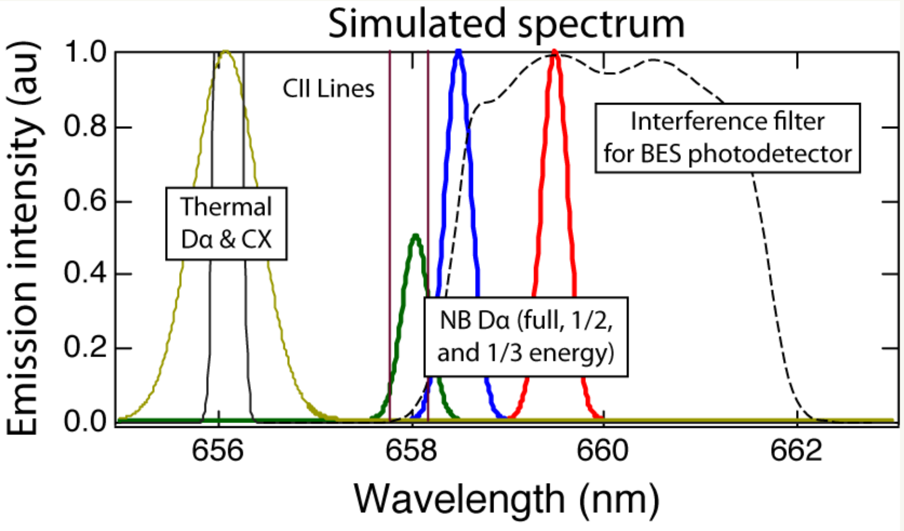
The pedestal sets boundary conditions for the core and ejects structures that damage plasma-facing components

- Projections for ITER depend on accurate pedestal models
  - **ST parameter regime** (large ρ^*, high β, shaping, beam-driven flow) is a challenging environment for pedestal simulations
- **Pedestal turbulence measurements** in NSTX H-mode plasmas during ELM-free, MHD quiescent periods
  - Identify **parametric dependencies** between turbulence quantities and transport-relevant plasma parameters
  - Compare to turbulence models → scalings point to TEM turbulence
  - Compare to pedestal turbulence **simulations**



Turbulence measurements
in steep gradient region

Beam emission spectroscopy (BES) measures Doppler-shifted D_α emission from neutral beam particles

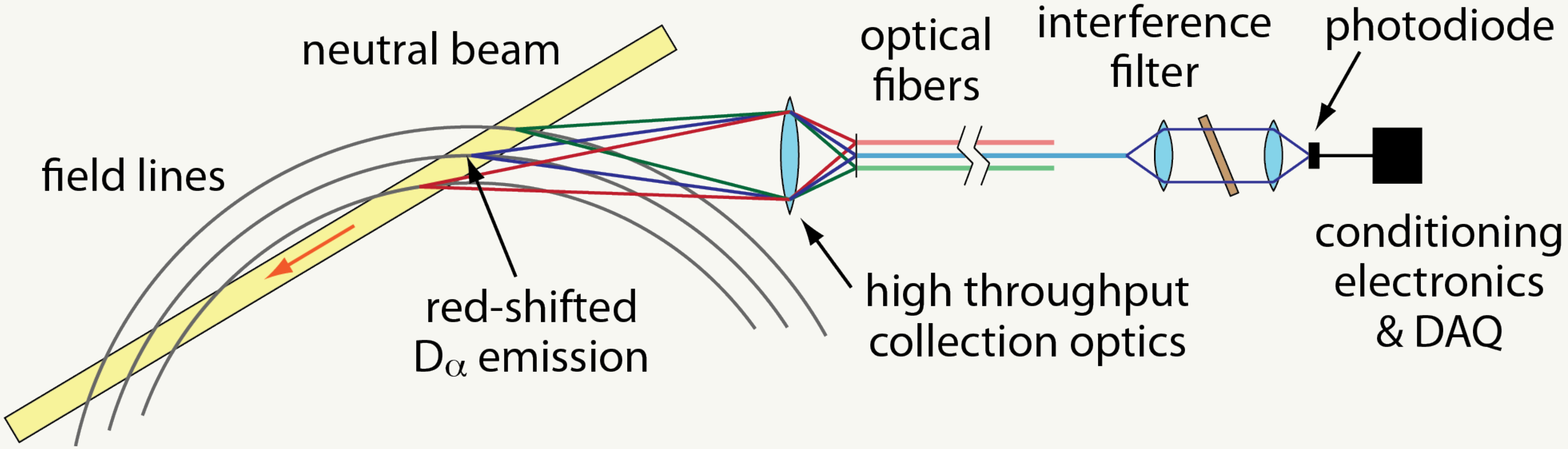


$$\frac{\delta I_{D\alpha}}{I_{D\alpha}} = \frac{\delta n}{n} \times C\left(E_{NB}, n, T_e, Z_{eff}\right)$$

neutral beam D_α emission

density fluctuation

C ≈ 1/2



neutral beam

field lines

red-shifted D_α emission

optical fibers

interference filter

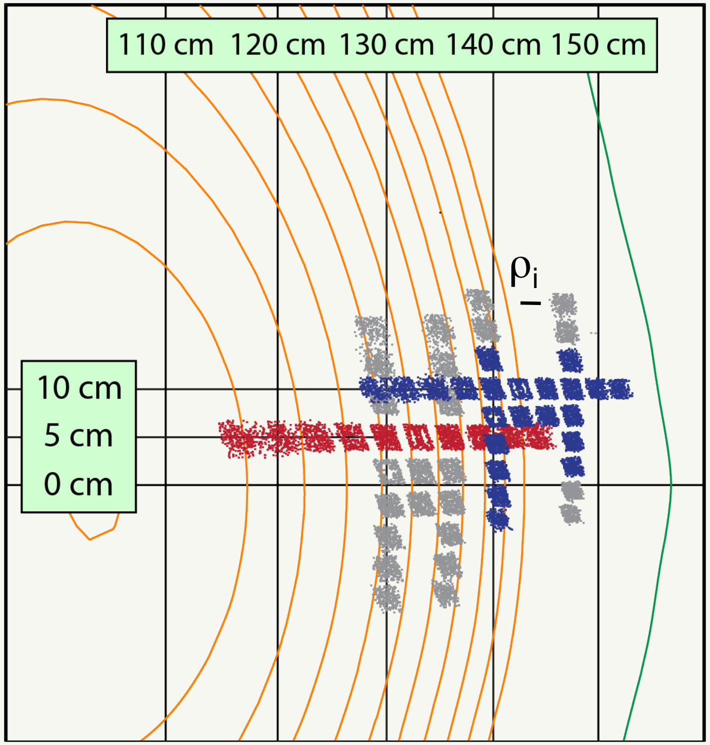
photodiode

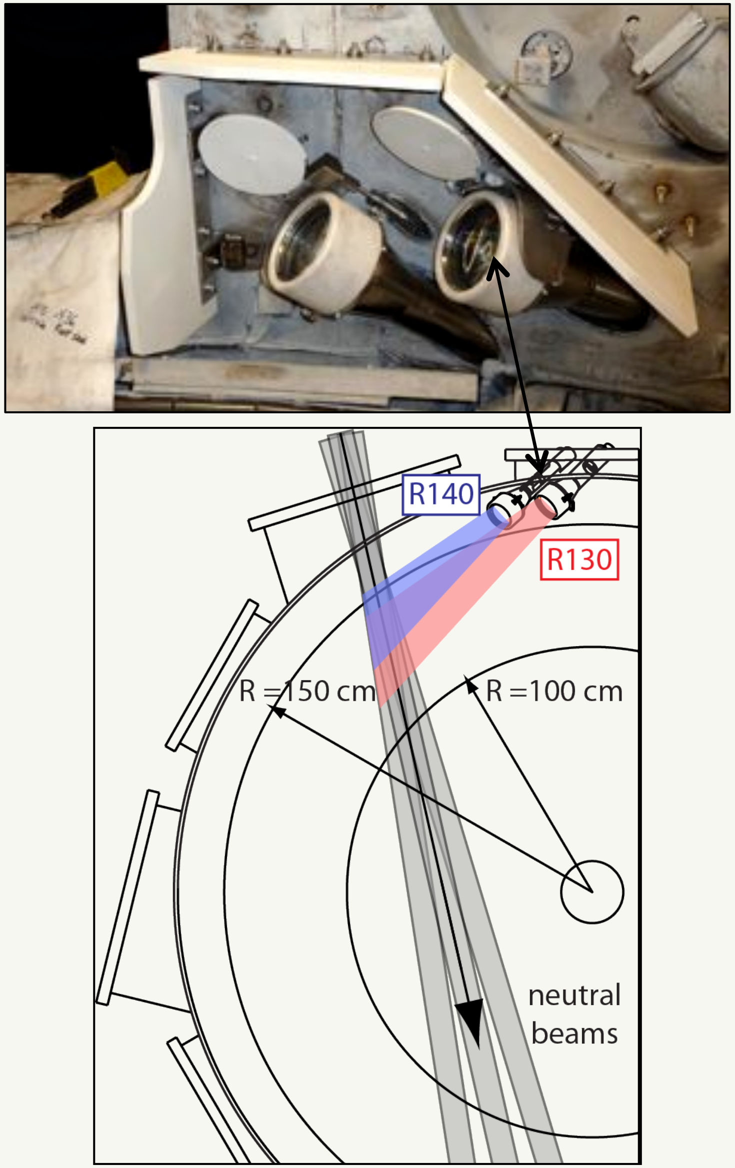
high throughput collection optics

conditioning electronics & DAQ

The beam emission spectroscopy (BES) system on NSTX measures fluctuations on the ion gyroscale with $k_\perp \rho_i \le 1.5$

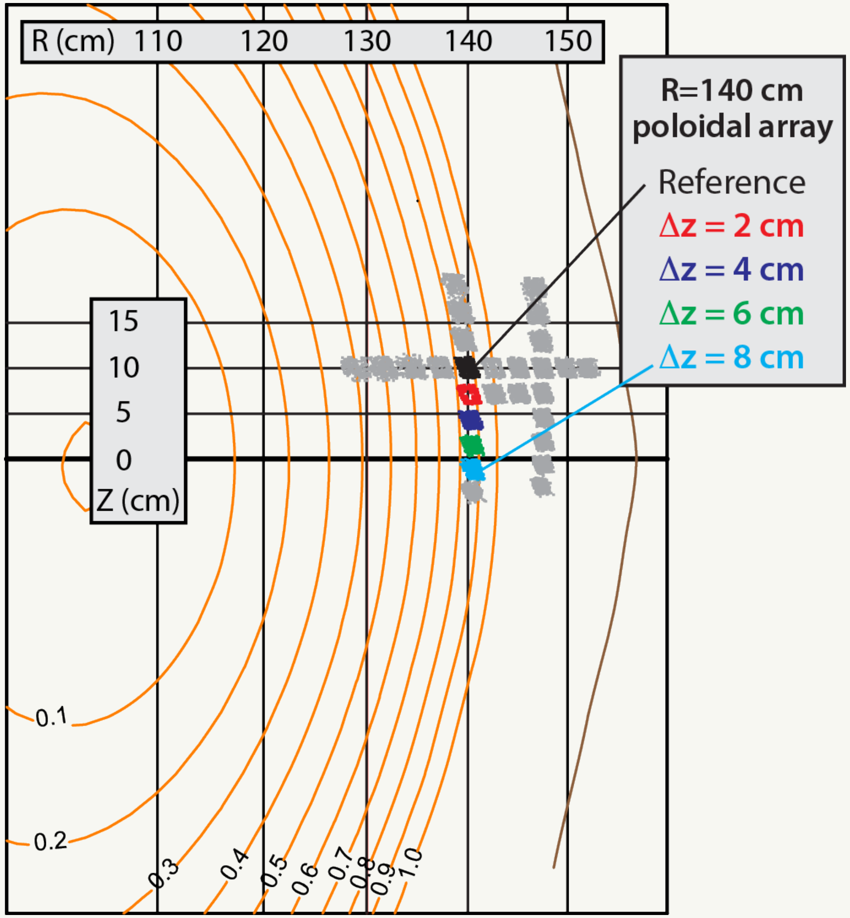
- Radial and poloidal arrays spanning core to SOL
- 32 detection channels
- **2-3 cm spot size and $k_\perp\rho_i \le 1.5$**

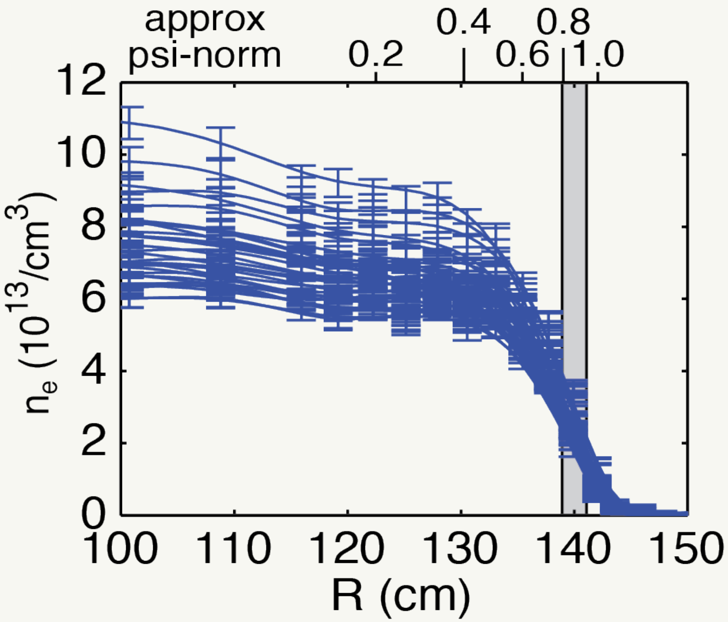




Pedestal turbulence measurements

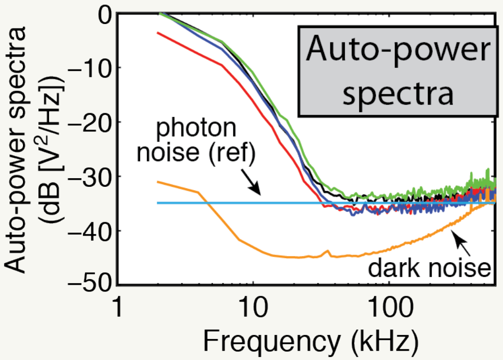
- ELM-free, MHD quiescent H-mode with Li conditioning
- $\Psi_N \approx 0.8 - 0.95$ in steep gradient region

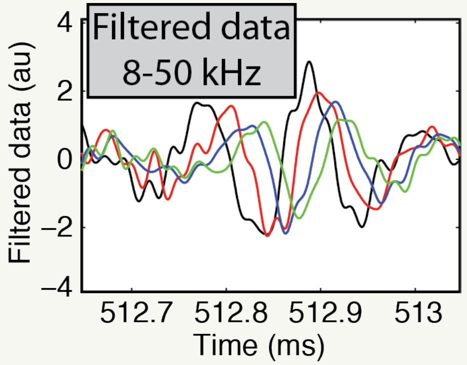




BES can measure poloidal correlation lengths (L_c), poloidal wavenumbers (k_θ), decorrelation times (τ_d), and amplitude ($\tilde{n}/n$)

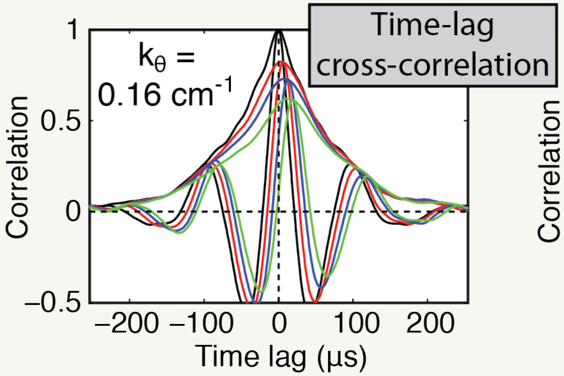
- Auto-power spectra show plasma turbulence signals above detector noise levels
- Filtered data (8-50 kHz) show eddies moving down BES array

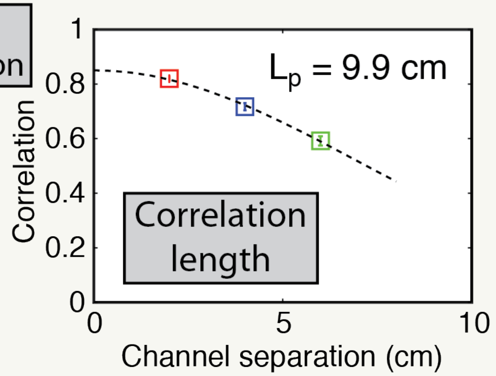


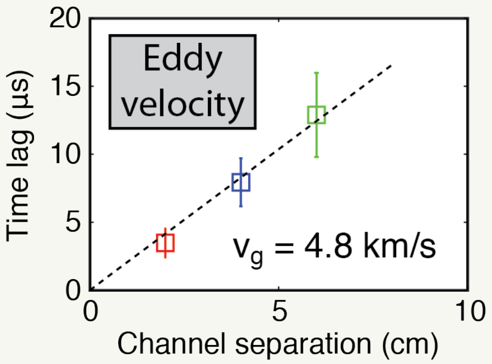


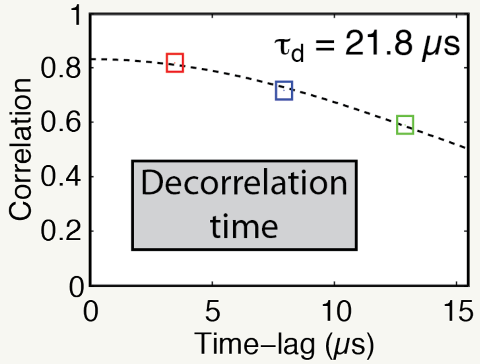
Time-lag cross-correlation gives:

- Correlation length $C(x,\tau=0)$
- Decorrelation time $C_{max}(\tau)$
- Eddy velocity $\Delta z/\Delta\tau_{lag}$
- Dominant wavenumber
  - Inferred from auto-correlation and eddy velocity

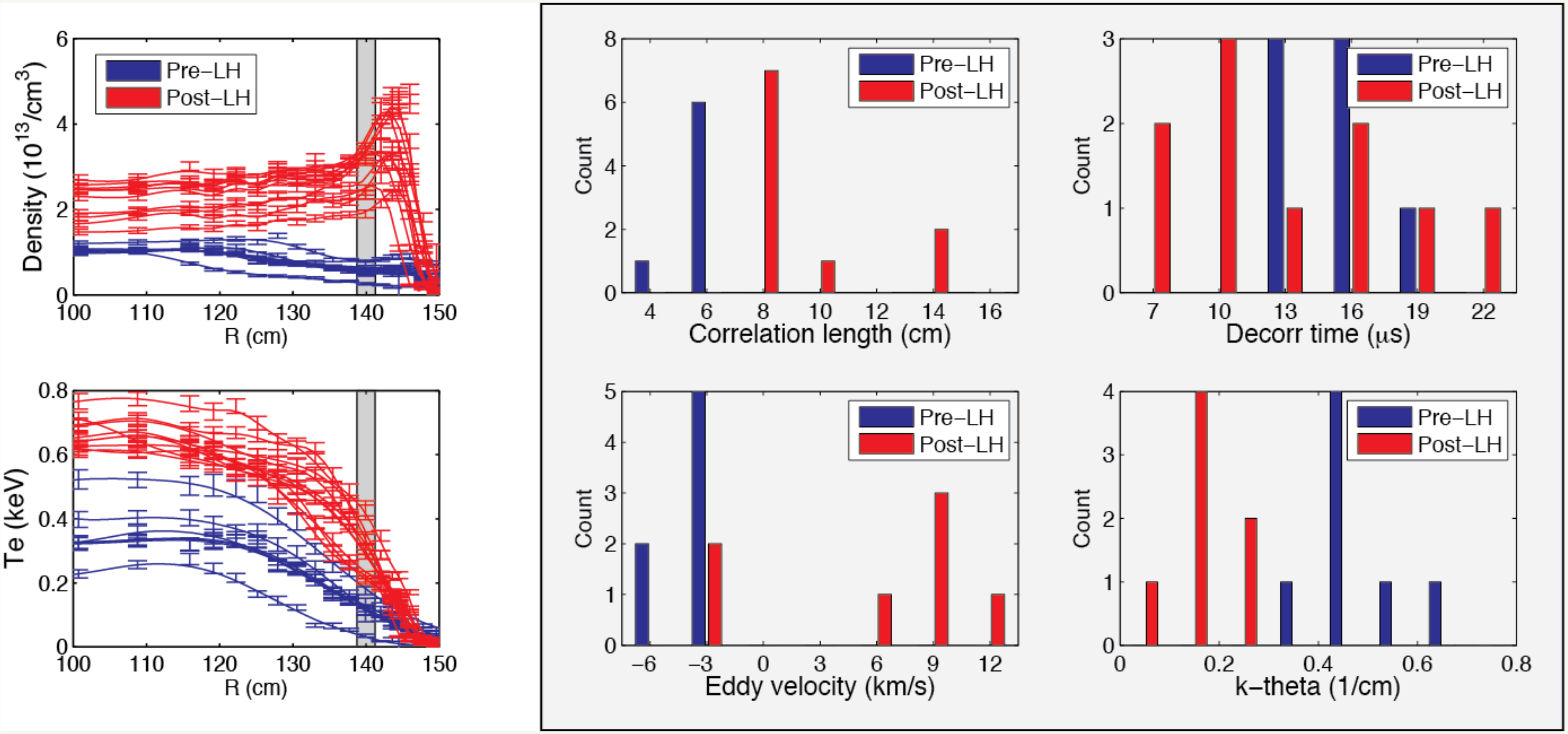








At the LH transition, L_{pol} increases and k_θ decreases

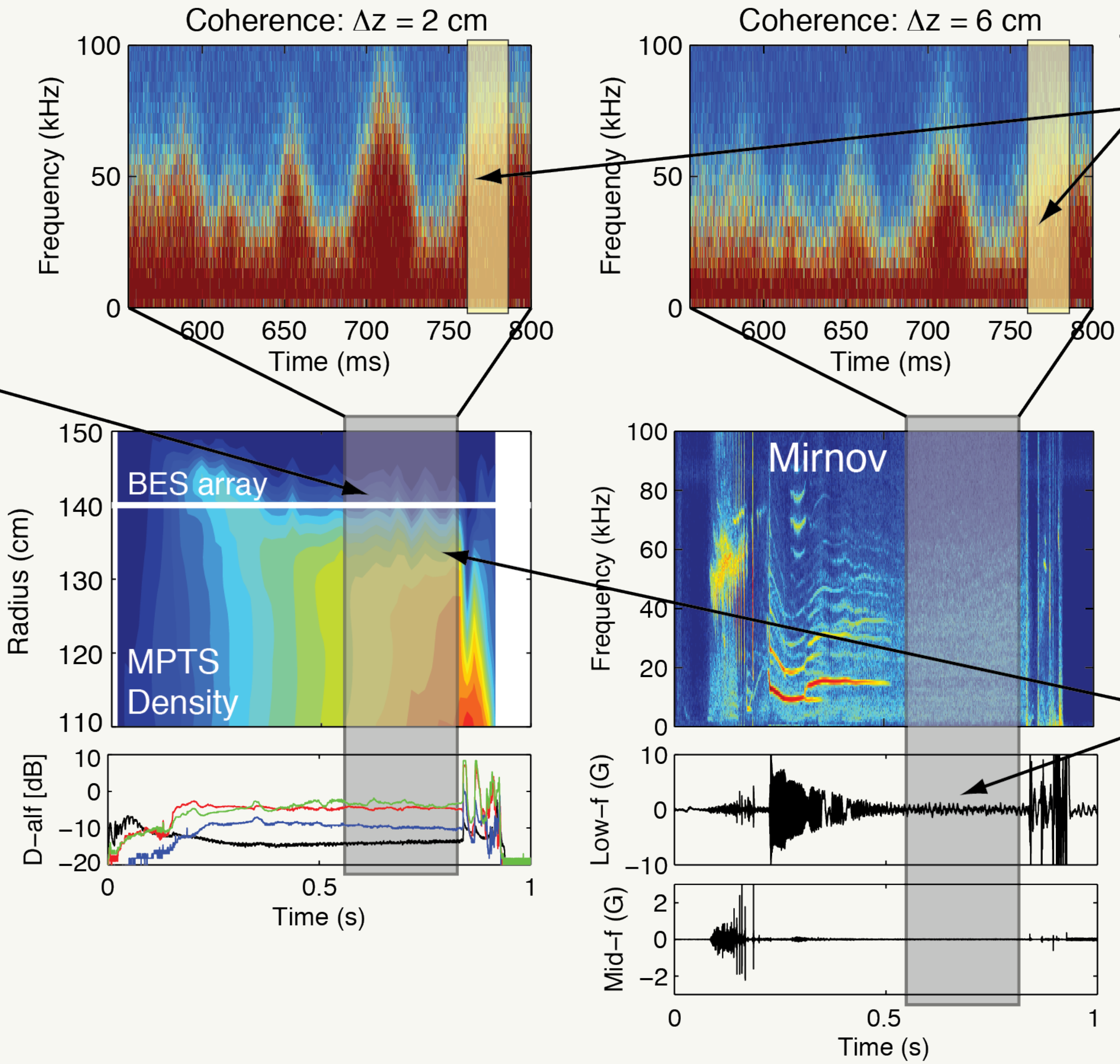


Also, measurements suggest eddy advection in lab frame shifts from *electron* to *ion* diamagnetic direction

ELM-free, MHD quiescent periods > 150 ms were identified and partitioned into 15-40 ms bins for turbulence analysis

Coherence for BES poloidally-separated channels

Slow plasma motion allows BES to sample across pedestal



Typical binning for analysis (15-40 ms)

Sustained ELM-free, MHD-quiesent period

Populated database with pedestal turbulence measurements and transport-relevant plasma parameters

- Database with 129 observations from 29 discharges

  B_{T0} = 4.5 kG

  I_p = 700-900 kA

  15-45 ms averaging
- Turbulence quantities are consistent with **DW turbulence**

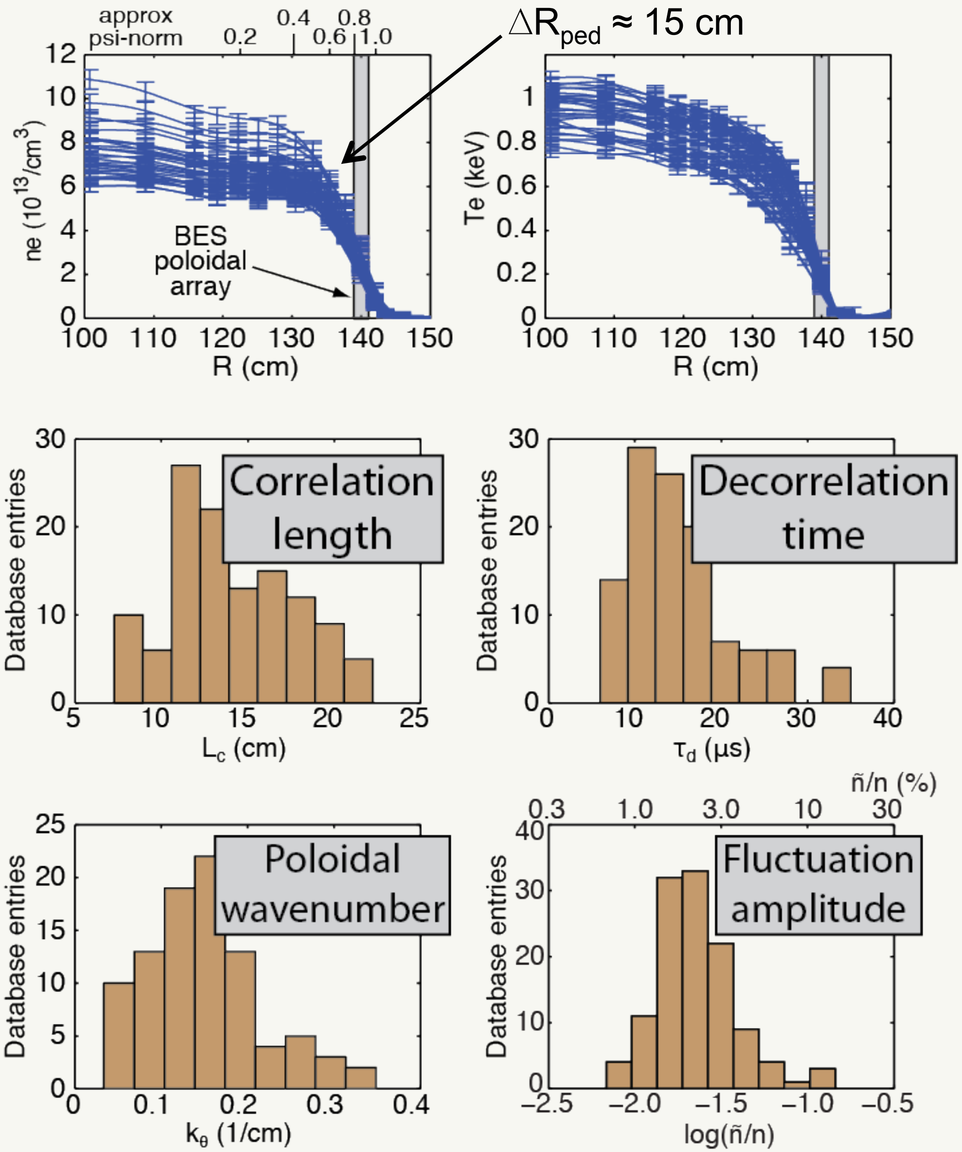
  $L_c/\rho_i \approx 8 – 18$

  $k_\theta \rho_i \approx 0.07 – 0.31$

  $\tau_d/(a/c_s) \approx 2.6 – 6.5$

  $\tau_d \omega^*_{pi} \approx 0.04 – 0.28$

  $\tilde{n}/n \approx$ 1%-4%
- Transport-relevant parameters
  - **n_e, ∇n_e, $1/L_{ne}$,** T_e, ∇T_e, $1/L_{Te}$, Ti, ∇T_i, $1/L_{Ti}$, v_t, ∇v_t, q, $\hat{s}$, ν_e, ν_i, β, β_e, n_{ped}, ΔR_{ped}, δ_r^{sep}
  - generally 50%-300% variation



A search algorithm identified many linear regression models among turbulence quantities and plasma parameters

$$\frac{\hat{y}-\bar{y}}{\sigma_y} = \sum \alpha_k \frac{x_k - \bar{x}_k}{\sigma_{xk}}$$

turbulence quantities

scaling coefficient

plasma parameters

- **Many models exist** in high dimensional x_k space
  - Models are error local minima
- Screen models for good statistics
  - **High statistical significance**
    t-statistics → $P(H_0\colon \alpha_k=0) < 5\%$
  - **Low multicollinearity**
    Pair-wise corr. → $\max(|C_{jk}|) < 0.6$
    Var. inflation factor → $\max(\text{VIF}_k) < 5$
  - **Normally distributed residuals**
    $P(\varepsilon)$ → Skew and Ex. Kurt. within 2σ
    Studentized residuals → no outliers

6 representative models for L_c/ρ_s

Model	α_k coefficients						
R^2	∇n_e	T_e	T_i	$1/L_{Ti}$	∇V_t	ν_e	n_{ped}
0.63	0.28	–	-0.20	-0.29	–	0.31	–
0.63	0.34	–	–	–	-0.37	0.30	–
0.61	0.46	-0.21	–	–	-0.38	–	–
0.60	–	–	–	–	-0.47	0.38	0.24
0.60	–	–	-0.22	-0.35	–	0.40	0.15
0.55	–	-0.24	–	–	-0.55	–	0.36

Should we try to identify a single “best” model?

Not a good idea because…

- Highly subjective
- Each model contains only a few (3-4) plasma parameters

Is there a better method?

Model aggregation is helpful when working with many possible predictor variables with complex interdependencies

Scalings are **robust** across models, regardless of number or combination of parameters in models

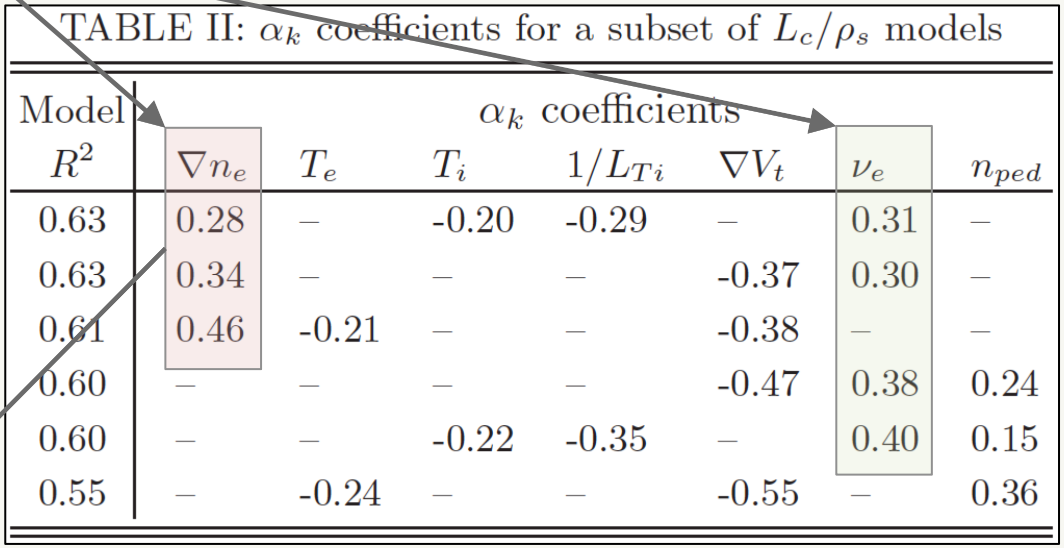
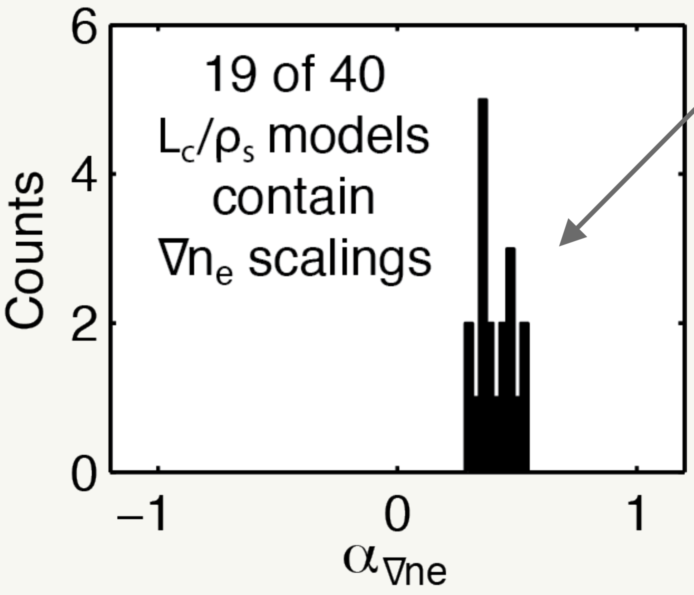


TABLE II: α_k coefficients for a subset of L_c/ρ_s models

Model	α_k coefficients						
R^2	∇n_e	T_e	T_i	$1/L_{Ti}$	∇V_t	ν_e	n_{ped}
0.63	0.28	–	-0.20	-0.29	–	0.31	–
0.63	0.34	–	–	–	-0.37	0.30	–
0.61	0.46	-0.21	–	–	-0.38	–	–
0.60	–	–	–	–	-0.47	0.38	0.24
0.60	–	–	-0.22	-0.35	–	0.40	0.15
0.55	–	-0.24	–	–	-0.55	–	0.36



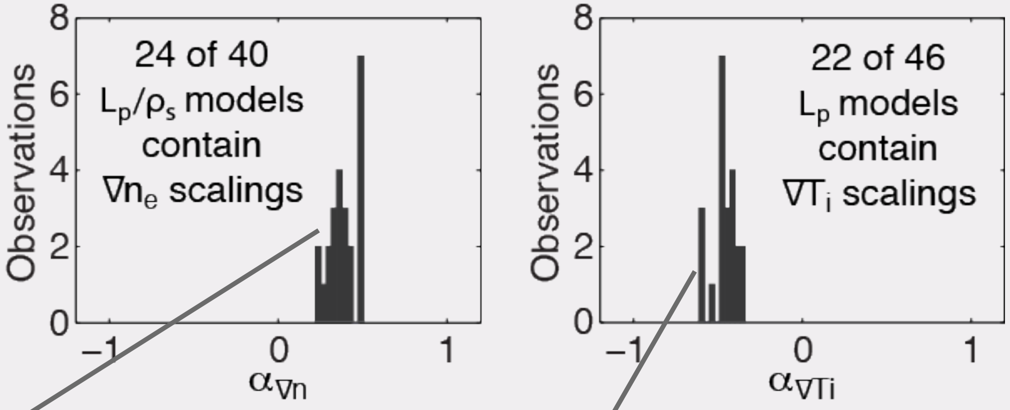
19 of 40 L_c/ρ_s models contain ∇n_e scalings

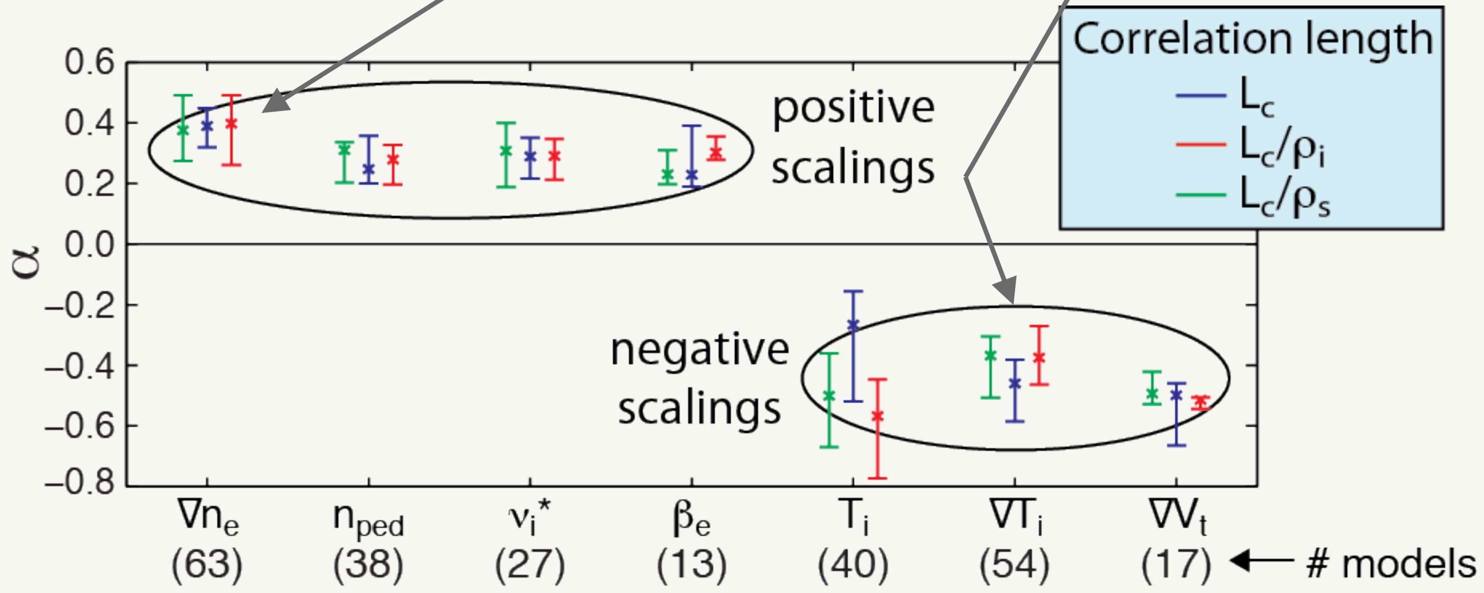
Model aggregation **advantages:**

- Identify more parameter scalings than single model
- Scalings are robust across different models

Model aggregation for L_c **increases** ($\alpha>0$) with ∇n_e, ν, β_e, and n_{ped}; L_c **decreases** ($\alpha<0$) with T_i, ∇T_i, and ∇V_t

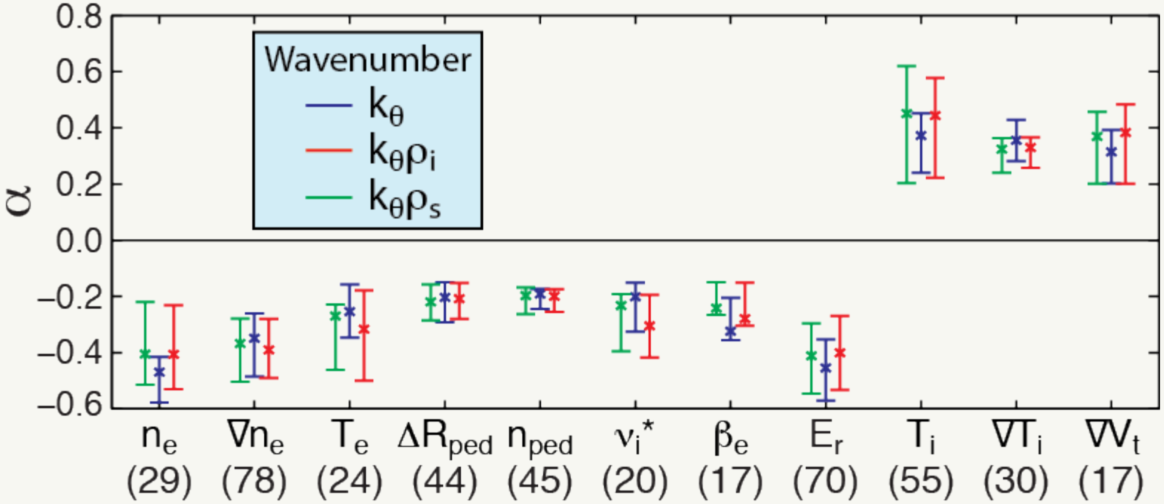
Scalings are robust across models with different parameter combinations

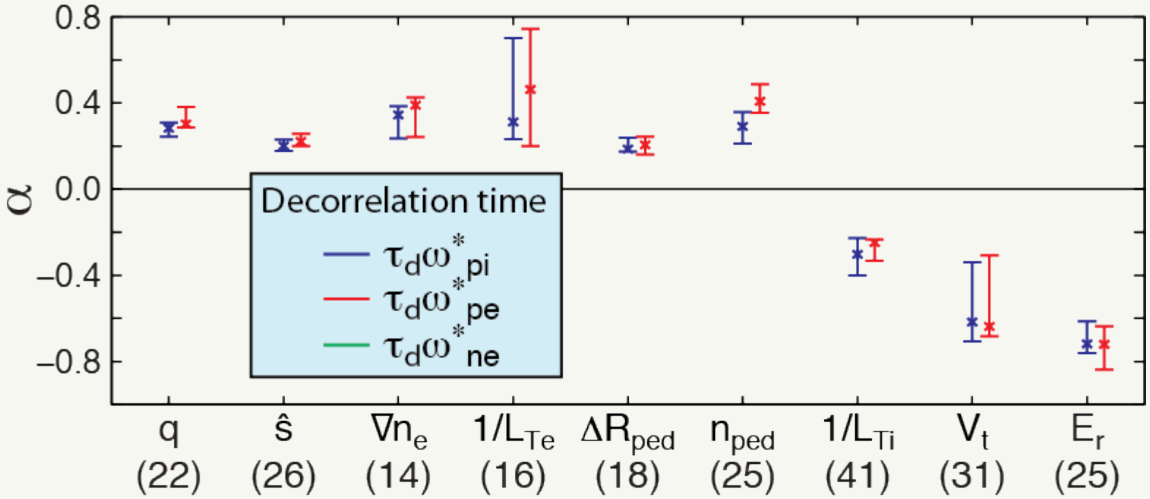




Observed scalings can help identify turbulent modes

k_θ scalings are opposite to L_c scalings as expected ($k_\theta \sim 1/L_c$ for broadband turbulence)





That's a lot of scalings, but what does it all mean?

Transport models link transport and turbulence quantities

Transport models (crude, but useful)

Random walk

$$D,\chi \approx \frac{L_r^2}{\tau_d} \approx \frac{L_p^2}{\tau_d}$$

Quasi-linear

$$D,\chi \approx \left(\frac{\gamma_l}{k_\theta^2}\right)_{\max\,\gamma}$$

Nonlinear mixing

$$D,\chi \approx \sum k_\theta \left|\Phi\left(k_\theta\right)\right|^2$$

$$\text{with } \left|\Phi\left(k_\theta\right)\right|^2 \propto k_\theta^{-\alpha} \text{ and } \alpha \approx 2-4$$

assume $L_r \propto L_p$ (random walk) and ignore cross-phases (nonlinear mixing)

- Trapped electron mode (TEM) turbulence
  - Theory (Peeters et al, PoP, 2005 and Lang et al, PoP 2007)
    - Driven by ∇n_e and ∇T_e
    - Stabilized by collisions and low T_e/T_i
    - Dissipative TEM (DTEM) requires collisions
  - Observed scalings
    - L_c increases and k_θ decreases with ∇n_e, **consistent** with TEM-driven transport
    - ν scalings point to **DTEM**, not collisionless TEM
    - T_e and T_i scalings are also **consistent** with TEM

ITG and KBM turbulence assessment

- Ion temperature gradient (ITG) turbulence
  - Theory (Kotschenreuther et al, PoP, 1995)
    - Driven by ∇T_i
    - Collisions, low T_e/T_i, and high ∇n_e are stabilizing
  - Observed scalings
    - ∇T_i, ∇n_e, and ν_i^* scalings are **inconsistent** with ITG-driven transport
    - However, T_i scalings are consistent with ITG

- Kinetic ballooning mode (KBM) turbulence
  - Theory (Snyder et al, PoP, 2001 and Guttenfelder et al, PoP, 2012)
    - Driven by ∇P with critical β_e
  - Observed scalings
    - β_e scalings are **consistent** with KBM-driven transport
    - ∇T_i, $1/L_{Te}$, and ∇n_e scalings show mixed agreement

μ-tearing assessment and recap

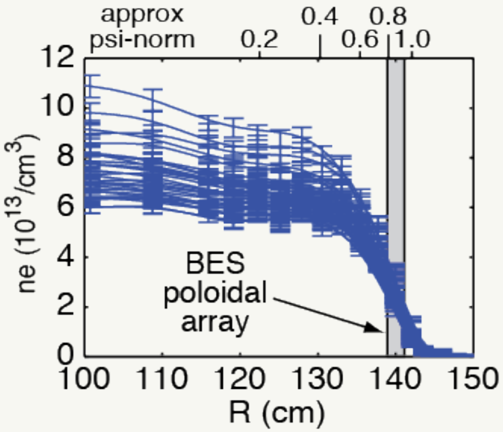
- Microtearing (MT) turbulence
  - Theory (Guttenfelder et al, PoP, 2012)
    - Driven by ∇T_e
    - Enhanced with collisions and higher β_e
  - Observed scalings
    - β_e and ν scalings are **consistent** with MT-driven transport
    - $1/L_{Te}$ scalings τ_d are inconsistent with MT-driven transport
  - Note: NSTX core turb. simulations indicate BES would be insensitive to μ-tearing, but pedestal simulations point to mixed-parity modes

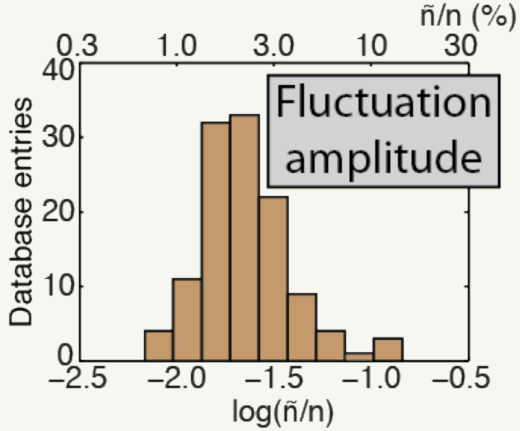
- Recap: Observed scalings are …
  - Partially consistent with **TEM**, **KBM**, and **MT**-driven transport
  - Least consistent with **ITG**-driven transport

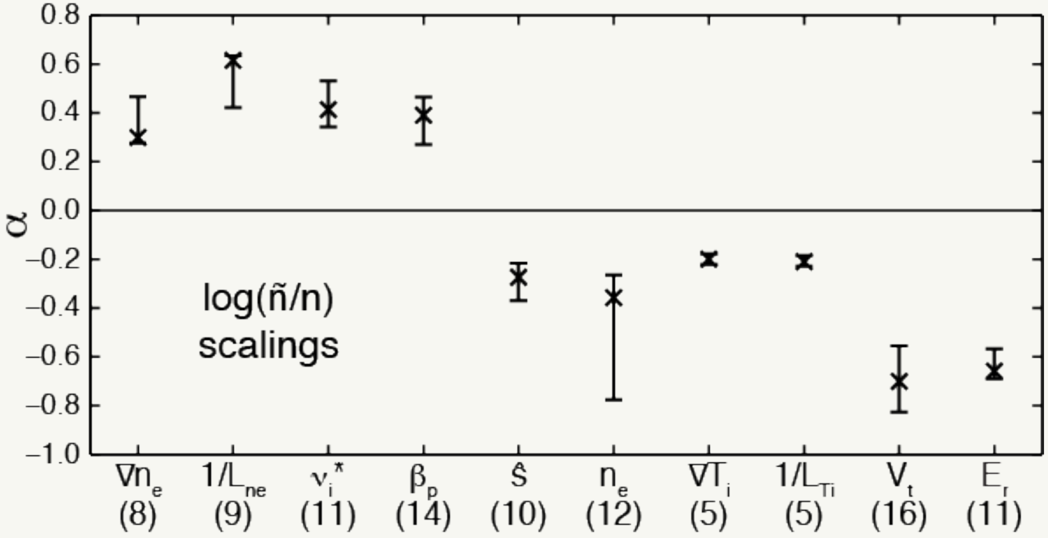
Turbulence reduction by equilibrium and zonal E×B flows can be inferred from observed scalings

- ∇v_t scalings for L_c and k_θ consistent with turbulence suppression by **equilibrium E×B flow shear**
  - L_c decreases and k_θ increases at higher ∇v_t
- E_r sclaings for τ_d are **consistent** with turbulence decorrelation by ExB flow shear
- Collisionality scalings **consistent** with collisionally-damped **zonal flows**
  - L_c increases at higher ν
- n_{ped} and ΔR_{ped} scalings **consistent** with empirical relationship between wider pedestals and larger turbulent structures (Z. Yan et al., PoP 18, 056117 (2011))

Recent ñ/n scalings reinforce previous results



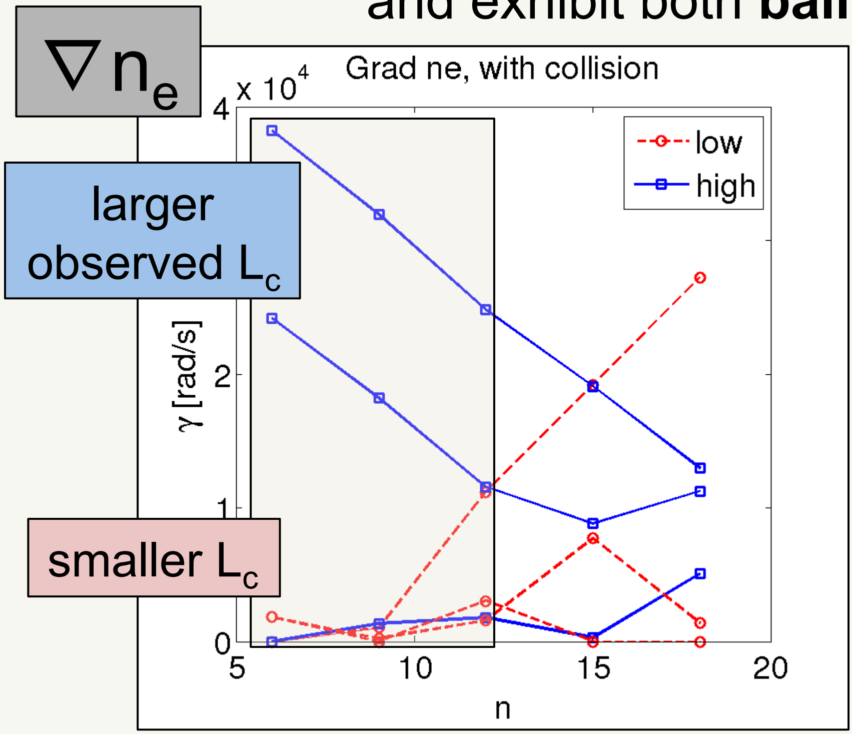




- Most consistent with **TEM**, **KBM**, and **MT** instabilities
- Least consistent with **ITG**
- Positive scalings with
  - ∇n_e and $1/L_{ne}$
  - ν_i^* (and other ν quantities)
  - β_p
- Negative scalings with
  - ∇T_i and $1/L_{Ti}$
  - $\hat{s}$
  - E_r and V_t
- Scalings consistent with equilibrium and zonal ExB turbulence suppression.
- Scalings consistent with larger ñ/n at edge.

Linear growth rates from GEM gyrokinetic simulations show scalings consistent with measured L_c scalings

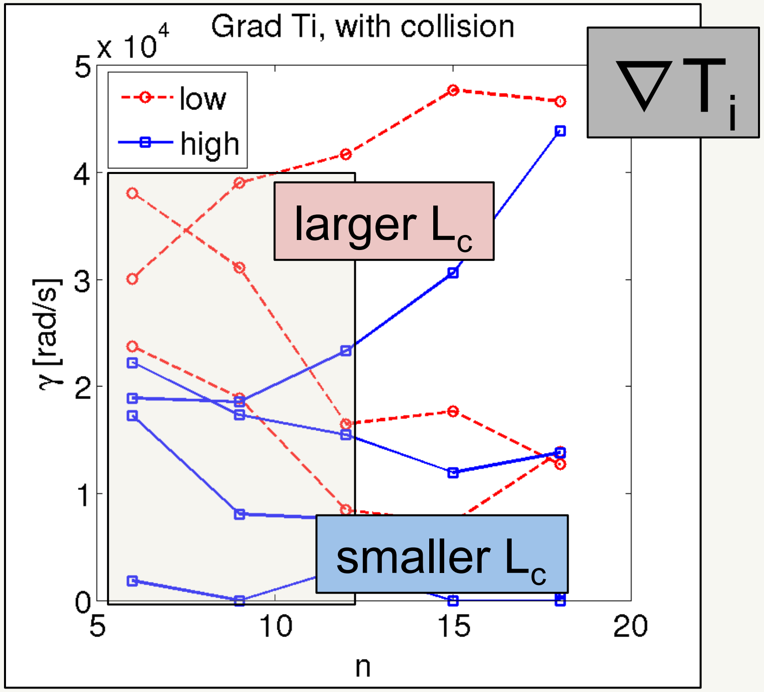
GEM* global (pedestal) simulations with $6 \leq n \leq 15$ and $k_\theta \rho_s \sim 0.2$ indicate instabilities are **electromagnetic**, destabilized by **collisions**, and exhibit both **ballooning** and **tearing parity**


∇n_e

larger observed L_c

smaller L_c

5 of 6 ∇n_e scenarios indicate low-n growth rates increase at higher ∇n_e


∇T_i

larger L_c

smaller L_c

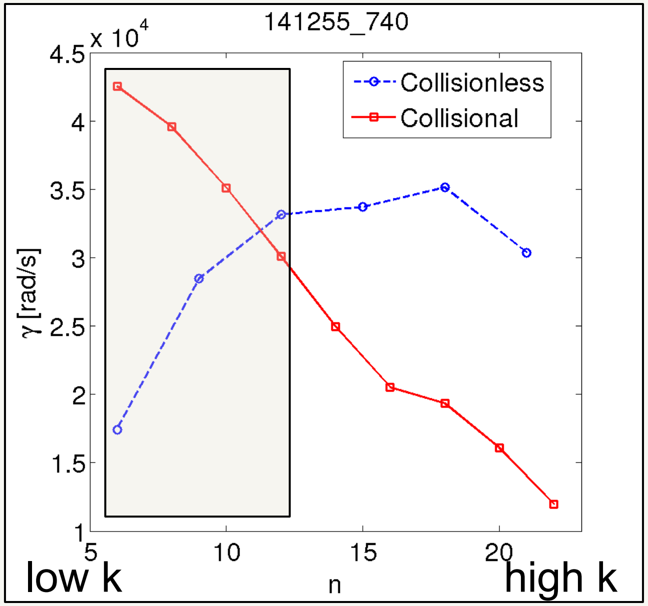
7 of 7 ∇T_i scenarios indicate low-n growth rates decrease at higher ∇T_i

GEM γ dependencies on ∇n_e and ∇T_i are consistent with observed L_c scalings

* Y. Chen and S. Parker, J. Comp. Phys. 220, 839 (2007)

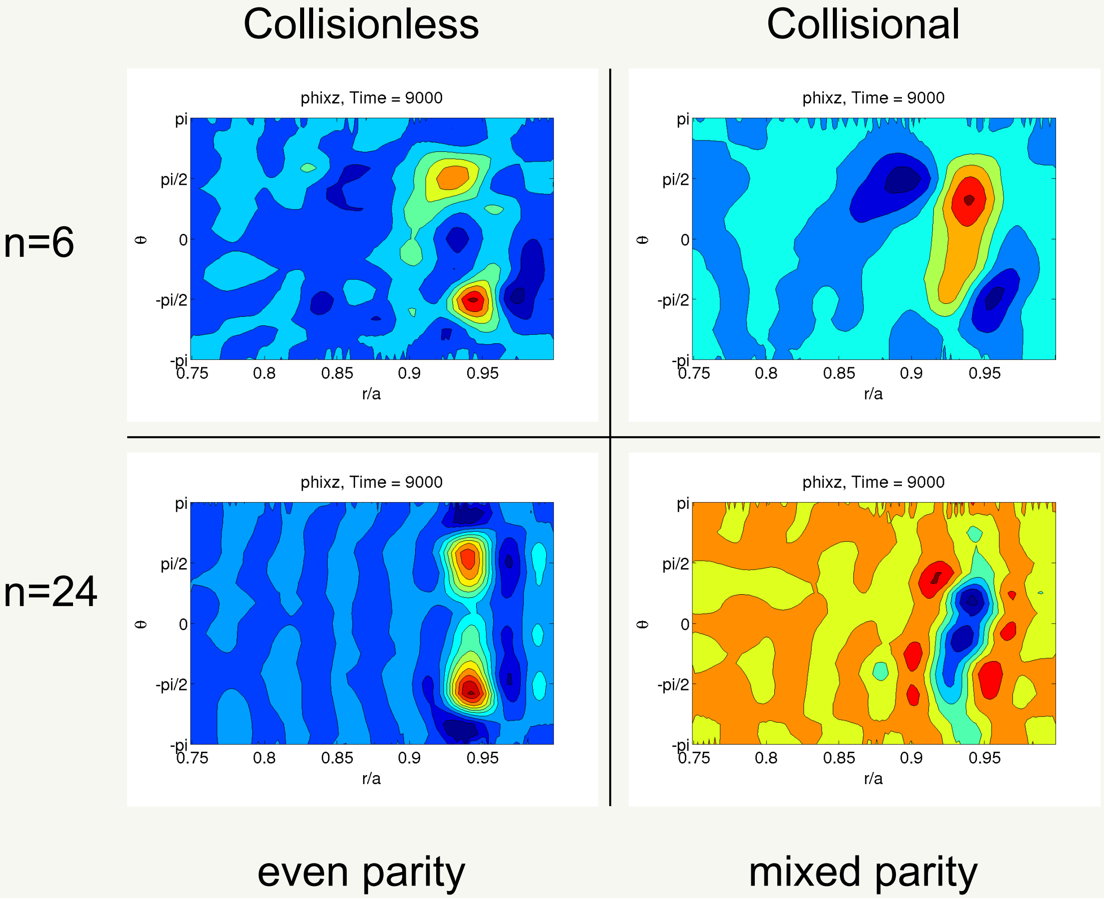
Linear GEM simulations point to **mixed-parity** modes and highlight the importance of **collisions**

Collisions increase γ at low-n (decrease γ at high-n)



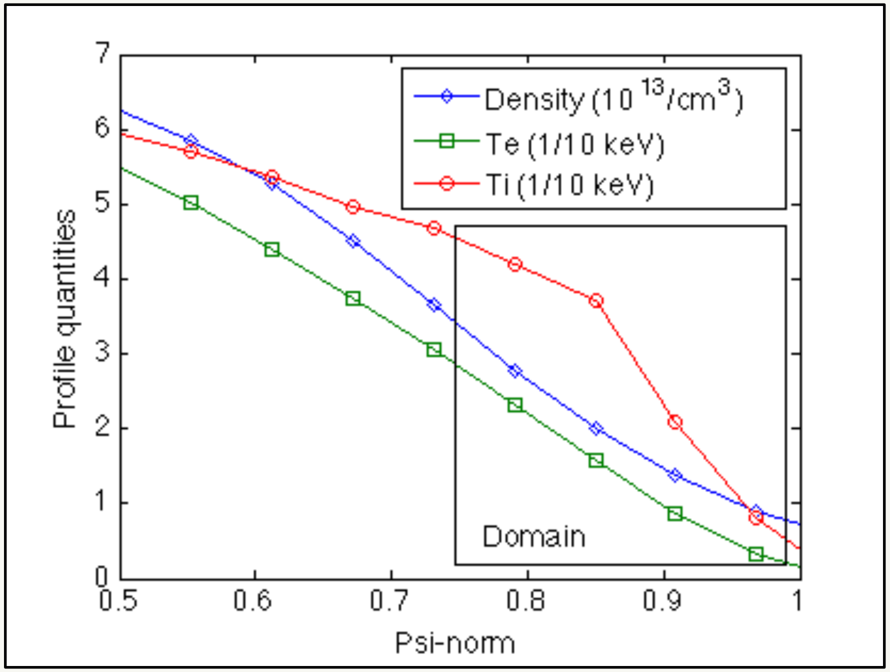
Low-n modes consistent with observed scalings that show lower k_θ at higher ν

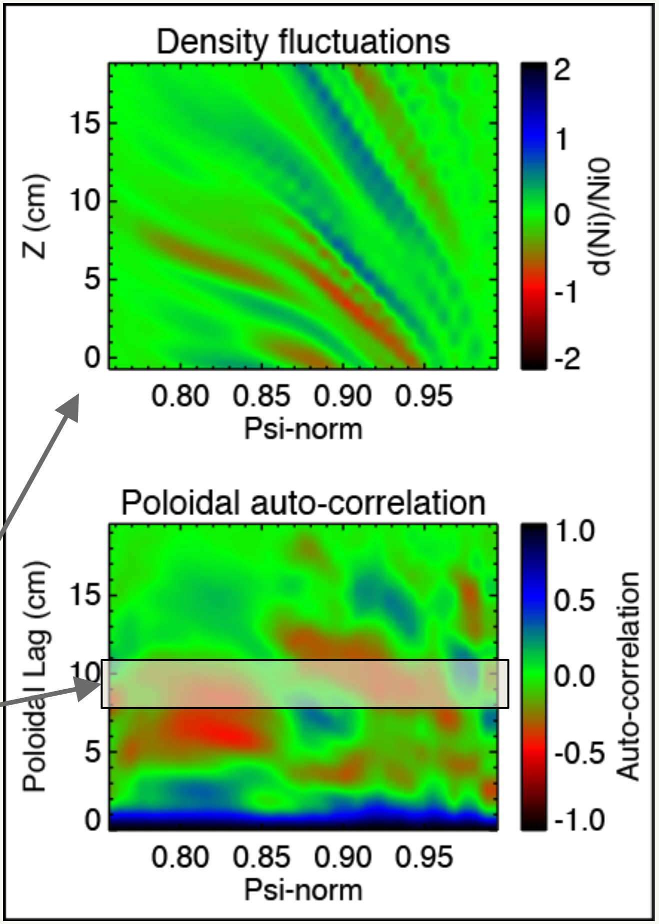
GEM ϕ contours in plane ⊥ B (n=6)



L_c and k_θ from BOUT++ pedestal simulations compare favorably with measurements

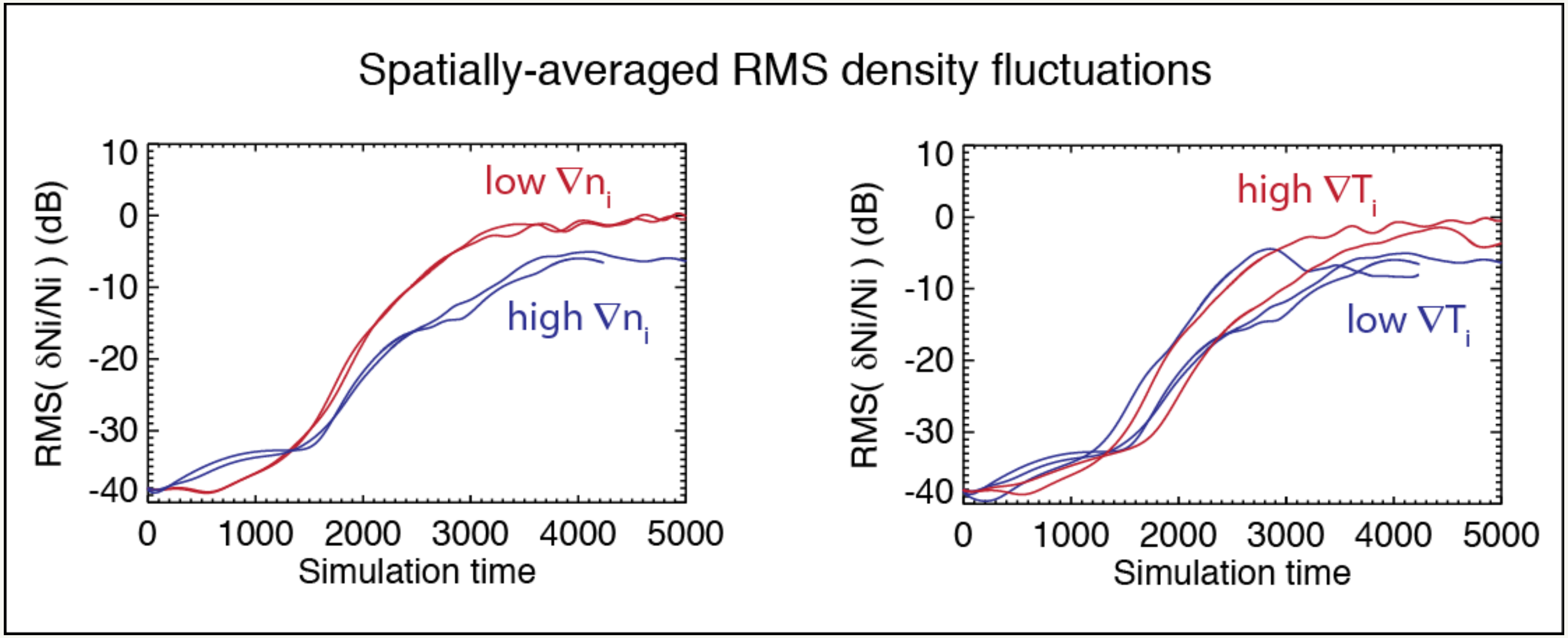
Initial value 3D Braginskii fluid simulations evolve n_i, ω, $j_{||}$, $A_{||}$, T_i, and T_e with collisionality, E×B advection, field line curvature, and drive terms for $j_{||}$ and ∇P. Simulations do not include toroidal rotation and parallel advection.





L_c/ρ_i ~ 8 is in line with measurements, but $k_\theta \rho_i$ ~ 0.7-1.4 is higher than measurements

BOUT++ parameter scans point to larger fluctuation amplitudes at **lower** ∇n_i and **higher** ∇T_i



- ∇n_i and ∇T_i trends from Braginskii model do not reproduce observed scalings
  - Highlights the importance of **electron dynamics** for TEM and MT physics
  - Demonstrates that simple, order-of-magnitude comparisons (e.g. correlation length) can lead to erroneous inferences
  - Will benefit from BOUT++ **gyrofluid** model → X. Xu et al, in press, PoP (2013)

Summary

- ST parameter regime can extend the parameter space and confidence in pedestal models
- We measured pedestal turbulence parameters in NSTX H-mode plasmas during ELM-free, MHD quiescent periods (with Li conditioning)
  - **$L_c/\rho_i \sim 12$ $k_\theta \rho_i \sim 0.2$ $\tau_d/(a/c_s) \sim 5$ $\tilde{n}/n \sim 1\%\text{-}4\%$**
- Parametric dependencies for pedestal turbulence measurements are most consistent with **TEM turbulence** and partially consistent with **KBM and μ-tearing turbulence**
  - **GEM** gyrokinetic simulations show linear γ scalings **consistent** with measure L_c scalings for ∇n_e and ∇T_i

Future work

- Extend measurements and analysis to radial L_r and k_r
- Radial and poloidal wavenumber spectra
- Flow fluctuations and time-delay estimation
  - Predator-prey model between flow fluctuations and turbulence parameters
- Nonlinear global (pedestal) gyrokinetic and gyrofluid simulations